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Advanced fire detection using multi-signature alarm algorithms ☆

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Abstract

The objective of this work was to assess the feasibility of reducing false alarms while increasing sensitivity through the use of combined conventional smoke detectors with carbon monoxide (CO) sensors. This was accomplished through an experimental program using both real (fire) and nuisance alarm sources. A broad selection of sources was used ranging from smoldering wood and flaming fabric to cooking fumes. Individual sensor outputs and various signal-conditioning schemes involving multiple sensors were explored.

The results show that improved fire-detection capabilities can be achieved over standard smoke detectors by combining smoke measurements with CO measurements in specific algorithms. False alarms can be reduced while increasing sensitivity (i.e., decreasing the detection time for real fires). Patented alarm criteria were established using algorithms consisting of the product of smoke obscuration and the change in CO concentration. Alarm algorithms utilizing ionization detector smoke measurements proved to be more effective than measurements from photoelectric detectors. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Alarm algorithms; Smoke detection; Fire detection; Carbon monoxide detection; Multi-signature alarm

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1. Introduction

The objective of this work was to demonstrate the potential of a combined CO/smoke detection algorithm, which is capable of discriminating between signatures from real fire and nuisance sources. The main goal was to provide faster response to real fire threats while providing better nuisance alarm immunity compared to conventional smoke detectors. The overall experimental work plan involved the development and testing of a prototype combined CO/smoke detector. This work was divided into several tasks, which included evaluation of appropriate CO sensor technologies, measurement of multiple fire signatures from incipient fire and nuisance sources, detection tests with larger sources, detection tests in a UL217/EN54 test facility, and analysis of the data for development of signal-processing algorithms. This paper presents the work based on the incipient fire and nuisance source testing.

2. Background

The application of multi-criteria fire-detection technology primarily started with the introduction of addressable analog detectors. Advances in microprocessor electronics first allowed detectors to be more intelligently monitored and controlled by a supervisory control panel. In more recent years, further advancements in microprocessor electronics have allowed the development of intelligent detectors. In this case, data processing can occur in the detector itself, independent of the control panel.

The use of multi-criteria-based detection technology continues to offer the most promising means to achieve both improved sensitivity to real fires and reduced susceptibility to nuisance alarm sources [1–4]. A multi-criteria detection system can be developed by properly processing the output from sensors that measure multiple signatures of a developing fire or by analyzing multiple aspects of a given sensor output (e.g., absolute value, rate of rise or fluctuation). For example, Pfister [5] reports on the work in which better discrimination between smoke and water vapor is achieved with an ionization chamber by comparing ion current output at both low and high voltages. A majority of the work in the area of multi-criteria fire detection has focused on processing data from multiple sensors (i.e., multi-signature detection) [2–4,6–15]. Much of this research has focused on the development of alarm algorithms using fuzzy logic and neural networks for event classification and discrimination between fire and nuisance sources [6–10,16]. Based on the work to date, the use of gas sensors in combination with smoke sensors holds the greatest potential for successful multi-criteria detectors.

Currently, there are no combination gas/smoke detectors on the market. The commercially available multi-sensor detectors are combinations of thermal and smoke sensors. Unfortunately, there has been no published data that clearly demonstrate the advantage of these commercially available detectors over single photoelectric and ionization detectors. The work presented in this paper

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demonstrates the performance advantages in fire detection and discrimination of a CO/smoke detector compared to commercial photoelectric and ionization smoke detectors. This improvement is achieved with a simple approach to alarm algorithm development.

3. Experimental setup and procedure

The majority of tests performed consisted of small incipient sources in a 49 m^3 (1730 ft^3) test room. The compartment was 5.87 x 3.43 x 2.44 m^3 high (19.25 x 11.25 x 8 ft^3). Natural ventilation was provided through a 38 cm x 30 cm duct located at the floor in the front right corner of the room. The sources were located 0.61 m from the center of the right wall. Smoke detectors and sensors were mounted at the ceiling, centered in the compartment at a distance of about 4.57 m (15 ft) from the source. Smoke detectors consisted of Simplex ionization detectors (Model 4098–9716) and Simplex photoelectric detectors (Model 4098–9701). A specially designed hardware/software package was used to poll the detectors every 4–5 s and save the data in a computer file.

Other sensors included various CO sensors, such as a City Technology Limited 3ME/F CiTicel carbon monoxide sensor with a range of 0–100 ppm (electrochemical cell), and a Telaire Systems, Inc. Ventostat (R) 2001 V CO_2 detector with a range of 0-5000 ppm (non-dispersive infrared). A gas-sampling probe was located next to the detector. Gas samples were analyzed by NDIR CO and CO_2 analyzers and a paramagnetic O_2 analyzer (Servomex 540A). The CO analyzer was a Horiba VIA-510 with a 100 ppm range and 1 percent of full-scale accuracy.

The results presented below are based on CO measurements from the continuous gas-sampling system which have been time-shifted for a 90 percent system-response time of 30s. Results using the real-time CO data from the City Technology electochemical cell sensor agreed very well with the time-corrected NDIR measurements.

Smoke-detector alarm conditions were set to be consistent with UL Standards 217 and 268 [17,18]. For the purpose of analyzing this data, the alarm criteria for the detectors were evaluated at typical values of 4.52 percent obscuration/m (1.4 percent/ft) for ionization and 6.72 percent obscuration/m (2.1 percent/ft) for photoelectric.

4. Selection of test sources

This phase of testing consisted of developing repeatable real alarm and nuisance sources, which challenged the detection limits of the commercial smoke detectors used in the test series. The main purpose of these tests was to develop a data base, which could be used to refine and evaluate multi-signature alarm algorithms. The two key criteria were to establish real alarm conditions for detector response-time performance and also conditions, which would cause commercial detectors to create nuisance alarms. A primary emphasis was placed on sizing the sources so that smoke levels and CO concentrations increased slowly with respect to time while maintaining test times to a minimum. The first column in Table 1 shows the sources that were tested.

5. General development of an alarm algorithm

There are several advantages of developing a combined CO/smoke detector. One of the primary advantages is the ability of a combined sensor algorithm to reduce

Table *1*
Summary of the number of alarms signaled by ionization and photoelectric smoke detectors compared to the alarm algorithm (Ion*CO≥10)

Source“	Ionization	Photoelectric	Ion*CO≥10
***Real** alarm*			
Heptane	7/7	0/7	7/7
Alcohol	0/3	0/3	0/3
Gasoline	5/5	5/5	5/5
Polyurethane	3/3	0/3	3i3
Cardboard	3/5	0/5	5/5
Cotton fabric	3/4	0/4	4/4
Cotton wick	2/2	0/2	2/2
PVC cable **(S)**	0/3	3/3	0/3
Cotton wick (S)	0/3	3/3	3/3
Wood *(S) 350°C*	0/3	3/3	0/3
Wood *(S)* **425°C**	0/3	3/3	1/3
Wood (S) *450°C*	0/3	3/3	3J3
Polyurethane *(S)*	1/3	3/3	3/3
Cotton batting *(S)*	0/3	3/3	3/3
Upholstery fabric (S)	1/3	3/3	333
No. detected/no. of tests	25/53	29/53	42/53
No. detected/no. of sources	8/15	9/15	12/15
Nuisance Alarms			
Wesson oil *(S)*	0/3	3/3	0/3
Toast **(S)**	3/3	3/3	3/3
Cheddar cheese (S)	0/3	2/3	0/3
Bacon *(S)*	1/3	3/3	0/3
Propane burner	0/2	0/2	0/2
Propane burner with H_2O pan	0/2	0/2	0/2
Kerosene heater	0/2	0/2	0/2
Cigarettes	3/3	2/3	3/3
People smoking	0/3	1/3	0/3
Steam	2/3	3/3	0/3
No. detected/no. of tests	9/27	17/27	6/27
No. detected/no of sources	4/10	7/10	2/10

“**(S)** indicates smoldering.

most nuisance alarms. Most nuisance alarms, which are not related to hardware problems, are the result of non-fire aerosols. Cooking aerosols, dusts, tobacco, and aerosol can discharges are examples of sources which cause nuisance alarms [19]. Cooking aerosols and steam (e.g., from a shower) are the most common nuisance alarm sources [20,21]. Of these examples, only tobacco smoke and possibly gas-fired cooking are expected to contain carbon monoxide. This makes carbon monoxide an attractive fire signature for detection purposes. The fact that carbon monoxide is the causative agent in a majority of fire deaths further enhances the desirability of using CO as a fire signature. Given the toxic properties of CO, it can be argued that a "false" alarm due to the actual presence of CO in non-fire situations is not a false alarm at all. Actually, such alarms are desirable for the general safety of building occupants.

The key to this advanced fire-detection technology is the development of a specific algorithm, which can effectively combine a CO sensor output (i.e., ppm CO) with that of a smoke detector such that nuisance alarms are eliminated and detector sensitivity to real fire sources is at least equal to, if not better than, current smoke detectors. An example of the general approach is depicted in Fig. 1, which shows a plot of smoke obscuration versus CO concentration. This plot illustrates several correlation strategies. Line 1 represents the alarm of a smoke detector set to 4.8 percent obscurationjm (1.5 percent/ft). Sources, which produce detector outputs lower than this value, are considered non-fire threats by the conventional ionization-type smoke detector.

Curve 2 represents the use of **"AND/OR"** logic which requires that the sum of the smoke measurement AND the CO concentration OR the smoke measurement OR the CO concentration reach a preset value. For this example, the alarm value is 10 (i.e., Smoke + CO = I0), the smoke is measured in percent obscuration/m, and the

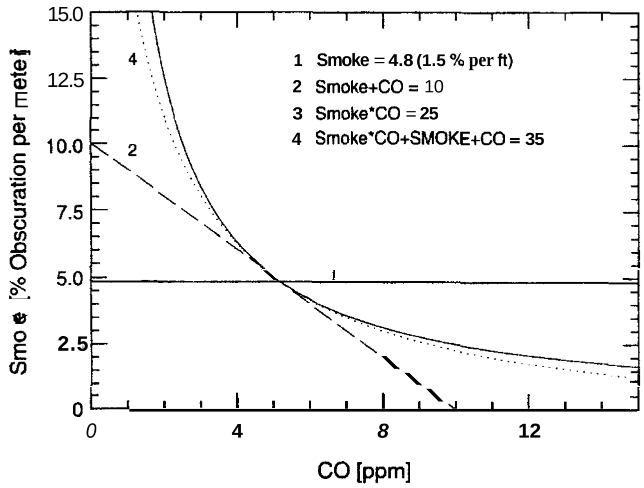

Fig. I. Smoke obscuration versus CO alarm criteria

CO concentration is measured as parts per million (ppm). Compared to curve 1, curve 2 effectively reduces the sensitivity of the smoke detector, when considered individually. The required smoke level for alarm is 10 instead of 4.8. Reducing detector sensitivity has been a common method for reducing nuisance alarms [19]. However, the reduced sensitivity can also result in much longer response times for real fires. Since fire growth is exponential, longer response times can translate into fire deaths. The inclusion in the correlation of a change in the CO level serves to reduce this response time effect while maintaining the original objective of reducing nuisance alarms. For example, in order to have an alarm with a smoke measurement of 5 percent/m, the measured increase in CO would have to be 5 ppm. Since most nuisance alarm sources do not produce CO, the correlation eliminates particle-producing, non-fire threat sources that fall below curve 2 in Fig. 1. This type of correlation can also provide faster alarm responses for fire threats in which CO is detected much faster than smoke.

A second correlation technique is to take the product of the smoke and CO measurements. In Fig. 1, curve **3** represents the product as a constant value of 25. For clarity, the curves in Fig. 1 have been arbitrarily drawn with a common point of tangency. Due to the asymptotic nature of this curve, a non-zero value for both smoke obscuration and the change in CO concentration is required to signal an alarm for this correlation. This characteristic is not desirable since there are fire sources, which can produce near-zero changes in the measured CO concentration (e.g., smoldering PVC cable). Therefore, in actual practice, this correlation would be combined with an alarm limit for both smoke and CO. **As** an illustration, an alarm condition would exist for a product greater than 25 or if the change in CO was greater than 20 ppm or the smoke level was greater than 10 percent/m.

This alternate method to eliminate the problem of near-zero smoke or CO measurements is actually a combination of curves 2 and **3** using the OR logic. A similar combination using AND and OR logic is represented by curve 4. For this example, the alarm level for the AND and OR combination is 35. Therefore, the two conditions can be represented as a single equation. This type of correlation states that an alarm condition is reached when the product of the smoke and CO outputs plus the individual outputs equals a set value (AND logic). An alarm will also be signaled if the product or one of the individual signals equals the alarm value (OR logic).

By selecting different alarm thresholds and various combinations of these correlations using Boolean logic, an infinite number of alarm curves can be created. Fig. 2 shows an example of an alarm curve created by combining curves 2 and 3 in Fig. 1 using OR logic with different alarm levels and weighting coefficients. Curve 2 in Fig. 1 has been changed so that the smoke measurement is weighted more in curve 2' of Fig. 2 (i.e., a line from 8 percent smoke to 12 ppm CO instead of a line from 10 percent smoke to 10 ppm CO). This change is representative of the decrease in the correlation sensitivity with respect to the CO component. This would tend to reduce nuisance alarms due to CO from tobacco smoke, for example.

The dashed and dotted lines in Fig. 2 represent the individual curves for the two correlations. The solid line represents the alarm correlation, which results from

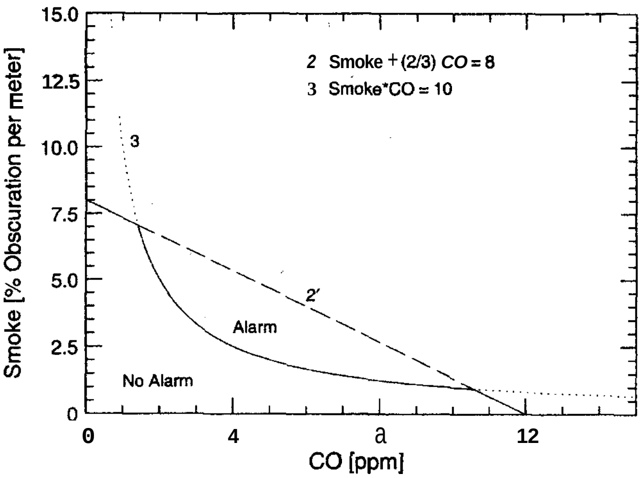

Fig. 2. Smoke/CO alarm criteria using combined curves

combining the two correlations using OR logic. An alarm is indicated if either condition 2' (Smoke + (2/3)CO > 8) OR condition 3 (Smoke*CO > 10) is true. This alarm correlation is more sensitive to fire sources that produce both smoke and CO than simply using curve *2'*. Also, it sets individual alarm limits for both smoke and CO. thus avoiding the asymptotic behavior of curve *3*.

6. Example of an alarm algorithm

Overall, the test results of more than 600 experiments have shown that a single optimal fire-alarm algorithm does not exist. Rather, the fire-alarm algorithm used for a fire-detection system is better tailored to the specific type of use (e.g., industrial, residential, kitchen, etc.). This is because certain applications place higher priority on improved sensitivity rather than reduced nuisance alarms, or vice-versa. Additionally, alarm algorithms differ depending on the type of smoke detector (ionization or photoelectric). Because of limited space in this paper and the large amount of data and analysis performed, this section only presents a summary of results for the incipient source tests and an example algorithm. The discussion focuses on an algorithm, which has proven to be effective in meeting the two primary goals of this program (i.e., better fire/nuisance source discrimination and shorter fire-alarm times). Preferred algorithms with greater performance capabilities have been developed. Additional information is provided in Ref. [22].

Table 1 presents a summary of the performance of the ionization and photoelectric smoke detectors in the $49\,m^3$ test compartment during the experiments using incipient sources. Table 1 shows, for each test source, the number of alarms signaled by each detector per number of tests conducted for that source. The smoke detectors were considered to be in alarm at 4.52 percent obscuration/m for the ionization detector and 6.72 percent obscuration/m for the photoelectric. At the bottom of each column in Table 1 are two totals indicating the number of alarms signaled per total number of tests and the number of alarms signaled per total number of different sources.

As expected, the ionization detectors were better at detecting flaming fires, and the photoelectric detectors were better at detecting smoldering sources. For example, the ionization detectors were unable to detect the smoldering fires, such as PVC cable, cotton wick, and wood; the photoelectric detectors were unable to detect flaming fires of sources such as heptane, polyurethane foam, and cotton wick (Although detection was not achieved for some sources in these incipient tests, given longer duration or larger size sources, alarms may result. Therefore, these results should not be taken to be necessarily showing a limitation of each type of smoke detector.).

Numerous alarm algorithms were evaluated. Parameters that were studied included ionization and photoelectric smoke measurements, CO and CO_2 concentrations, and rate of rise of these variables. Generally, the algorithms that incorporated the ionization detector instead of the photoelectric detector signals were more effective overall. Some combinations of photoelectric and CO signals were able to detect more real sources than ionization and CO; however, this was accompanied by significant increases in nuisance alarms.

One algorithm that has proven to meet the goals of this program is based mainly on the criteria that if the product of the ionization detector output (percent obscuration/m) and the CO sensor (ppm) is greater than 10, a fire alarm is signaled. Table 1 also shows a summary of the fire detection and nuisance alarm performance of this algorithm (i.e., $\text{Ion}^*\text{CO} \geqslant 10$) compared to the performance of the ionization and photoelectric smoke detectors. The use of the alarm algorithm results in 17 additional real source tests being detected (42 out of 53 tests) compared to those of the ionization detector (25 out of 53 tests). The additional fires that were detected consisted of both flaming and smoldering sources. These results show that the alarm algorithm provides an increase in fire-detection sensitivity compared to both the ionization and photoelectric smoke detectors. **An** analysis of the response time results supports this conclusion as well.

Table 2 presents the times of alarm of the CO/smoke alarm algorithm and those of the ionization and photoelectric smoke detectors. The table is arranged according to the source type and test number. The last two columns compare the performance of the alarm algorithm with the performance of the ionization and photoelectric detectors. The alarm algorithm detected the real fire sources faster than the ionization detector in all but two tests (i.e., flaming heptane and polyurethane). These two incipient size sources produced a maximum of 2 ppm CO while producing significant quantities of smoke. The low CO to smoke production ratio makes these sources difficult to differentiate from many typical nuisance sources that produce aerosols (i.e., simulate smoke) and no CO. The difference in response times between the combined CO/smoke algorithm and the ionization detector ranged from 4 to 453s (7.5 min) for real alarm sources. For many of the sources expected in a

Table 2
Alarm response times of alarm algorithm ($Ion^{*}CO \geqslant 10$) compared to smoke detectors

Source	Test no.	Time to alarm (s)			Algorithm faster than ion	Algorithm faster than photo
		Ion	Photo	$Ion^{*}CO \geqslant 10$		
Real alarms						
Heptane	92	507		525	N	Y
	94	447		484	N	Y
	99	439		457	N	Y
	100	511		525	N	Y
	152	457		506	N	Y
	153	425		466	N	Y
	154	570			N	N/A
Alcohol	119				N/A	N/A
	121				N/A	N/A
	I24				N/A	N/A
Gasoline	93	140	434	131	Y	Y
	95	140	429	131	Y	Y
	97	167	412	145	Y	Y
	155	181	430	167	Y	Y
	156	167	511	158	Y	Y
Polyurethane	96	172		172	Same	Y
	98	168		177	N	Y
	101	181		185	N	Y
Cardboard	126	344		186	Y	Y
	129	375		163	Y	Y
	134			190	Y	Y
	146	429		244	Y	Y
	149			163	Y	Y
Cotton fabric	137	171		122	Y	Y
	140	254		136	Y	Y
	143	199		117	Y	Y
	145			181	Y	Y
Cotton wick	102	240		167	Y	Y
	123	222		168	Y	Y
PVC cable **(S)**	110		402		N/A	N
	112		402		N/A	N
	115		488		N/A	N
Cotton wick (S)	103		972	516	Y	Y
	105		706	426	Y	Y
	107		810	331	Y	Y

(continued on next page)

Table 2 *(continued)*

Source	Test no.	Time to alarm (s)			Algorithm faster than ion	Algorithm faster than photo
		Ion	Photo	Ion*CO$\geqslant$10		
Wood **(S)**	109		715		N/A	N
	111		665		N/A	N
	114		773		N/A	N
Wood *(S)* 425°C	178		185		N/A	N
	180		235		N/A	N
	182		181	326	Y	N
Wood *(S)* 450°C	179		177	249	Y	N
	181		190	199	Y	N
	183		186	204	Y	N
Polyurethane *(S)*	175		330	349	Y	N
	176		371	453	Y	N
	177	624	362	457	Y	N
Cotton batting *(S)*	169		515	533	Y	N
	170		633	542	Y	Y
	172		420		N/A	N
Upholstery fabric **(S)**	185		389	493	Y	N
	186	710	425	882	N	N
	189		438	615	Y	N
Nuisance **alarms**						
Wesson oil *(S)*	127		534		N/A	N
	130		619		N/A	N
	132		593		N/A	N
Toast **(S)**	104	380	502	412	N	Y
	106	384	457	407	N	Y
	108	416	516	457	N	Y
Cheddar cheese **(S)**	113		607		N/A	N
	116		538		N/A	N
	117				N/A	N/A
Bacon **(S)**	128		796		N/A	N
	131		824		N/A	N
	133	891	818		N	N
Propane burner	138				N/A	N/A
	141				N/A	N/A
Propane burner w/H_2O pan	139				N/A	N/A
	142				N/A	N/A
Kerosene heater	144				N/A	N/A

Table 2 *(continued)*

Source	Test no.	Time to alarm (s)			Algorithm faster than ion	Algorithm faster than photo
		Ion	Photo	Ion*CO≥10		
	150				N/A	N/A
Cigarettes **(S)**	136	72	131	72	same	**Y**
	147	72	113	72	same	Y
	148	141		77	Y	Y
People smoking	**162**				N/A	N/A
	167				N/A	N/A
	194		244		N/A	N
Steam	191	72	67		N	N
	192		82		N/A	N
	193	73	73		N	N

residential fire (e.g., smoldering fabric, polyurethane foam, and flaming cardboard). the combined alarm algorithm would afford the occupants several extra minutes of time to escape compared to smoke detectors alone. This additional time is significant in that most people typically have approximately 2–3 min to escape a fire after a smoke-detector alarm, [23].

Current smoke defectors can be made more sensitive to real fire sources, thus, reducing the time to alarm. However, this has been shown to be at the cost of creating more false alarms. The use of the alarm algorithm improved the fire-detection sensitivity while significantly reducing the occurrence of nuisance alarms. Table 1 shows that the alarm algorithm resulted in less nuisance alarms (6 out of 27 tests) than did the ionization detector (**9** out of 27) or the photoelectric detector (17 out of 27). The important point is that improvements were observed for two of the most common residential nuisance sources, cooking (i.e., the frying bacon tests), and steam. Considering that nuisance alarms in industrial environments can be due to dust and process particulate matter, which does not contain CO, the alarm algorithm would inherently provide nuisance alarm immunity in these environments where conventional smoke detectors may not.

Figs. *3* and 4 demonstrate how the CO/smoke alarm algorithm is able to provide improved sensitivity (i.e., faster response to fires) and immunity to nuisance sources compared to conventional smoke detectors. Fig. 3 shows how a real fire event moves diagonally away from the origin with time and cross the algorithm alarm level (at 117s) before the smoke alarm (199s). On the other hand, a nuisance source tends to produce a signature that lies close to the y-axis (particulate only) and crosses the smoke detector alarm level but not the CO/smoke algorithm alarm criteria (Fig. 4).

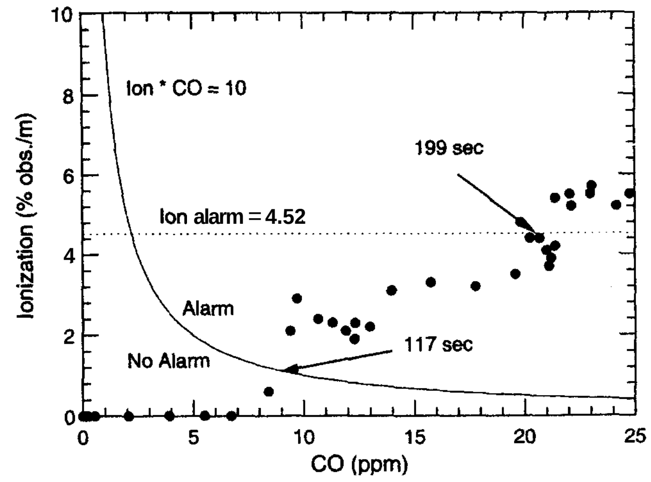

Fig. 3. Example of improved sensitivity with smoke/CO alarm algorithm for a cotton fabric fire.

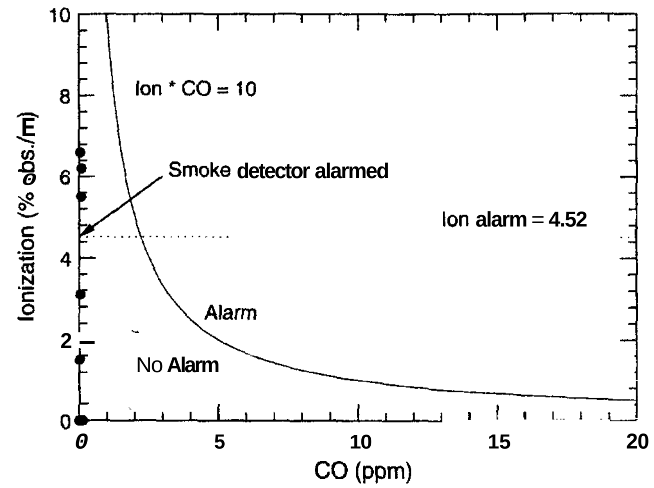

Fig. 4. Example of improved nuisance alarm immunity with smoke/CO alarm algorithm when exposed to steam.

7. Conclusions

Extensive testing and analysis has resulted in the development of a CO/smoke detector and multiple alarm algorithms, which can be optimized for the specific application of the detector for optimal performance. However, compared to conventional smoke detectors, general algorithms **do** exist that provide overall improved performance for a wide range of applications. For example, as presented in this paper, the CO/smoke detector with the alarm algorithm (Ion*CO$\geqslant$10) significantly improves life safety. The detector responds to real fire sources faster than a smoke detector, affording the occupants more time, up to several minutes, to escape a fire. Additionally, the multi-sensor detector eliminates many nuisance alarms.

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